AUTOMATIC ON-MACHINE MEASUREMENT OF COMPLEX PARTS

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Milling spindles with inserted 3D tensometric touch probes were applied for on-machine measurement of highly precise parts produced on three - and five-axis milling machines equipped with linear motors and direct rotary drives. New methods of CNC control of angular NC axes during measurement were developed for parts containing hardly accessible surfaces. In-process calibration of multi-directional accuracy of probes has resulted in submicron sensitivity and highest absolute accuracy of on-machine measurements.

Keywords
Machining, accuracy, on-machine measurement

1. Introduction

On-machine measuring (OMM), sometimes called on-machine inspection (OMI) or on-machine verification (OMV) means measuring of workpieces placed in the working space of the NC machine. Measuring can be performed after the final NC machining operation or between partial operations. For workpieces, machined on three-axis or five-axis milling machines, measuring is performed by a touch probe inserted into the milling spindle. Relative NC measuring movements between the spindle and the workpiece are programmed to touch the workpiece by the probe in measuring points pre-selected on the CAD model of the workpiece. Space direction of the final approaching movement is controlled to be perpendicular to the workpiece surface in measuring points. This makes it possible to compare the space positions of measured points with corresponding points selected on the CAD model and to evaluate errors of workpiece surfaces in normal direction to the surface.

Comparing with classical application of coordinate measuring machines, the on-machine measuring methods are exposed to a number of additional problems, connected with limited accuracy of production machines, thermal dilatations, clamping forces and dirty environment of the working space. On the other hand, the OMM methods can be very advantageous when applied on workpieces containing surfaces with limited accessibility, which can only be produced on five-axis milling machines. In such cases, a possibility exists to include NC control of rotary and tilting axes into the OMM measuring cycle and perform complete automatic and precise OMM measurement of very complex parts. Main advantage of such approach is that the measured workpiece is still located in proper position with respect to the linear and rotary NC axes of the machine, which reduces many otherwise necessary calibration and co-ordinate transformation procedures.

Within the last two years, the RCMT was developing just described OMM methods and verified on three highly precise milling machines, equipped with linear motors and direct rotary drives for best sensitivity of NC movements. The task was solved within a European project called Hardprecision during the 2006 and 2007 years. This paper describes main results of RCMT gained within the solution of this project.

2. Main problems and tasks

Measuring of complex workpieces with sculptured and hardly accessible surfaces needs to apply touch probes with best repeatability and "multi-directional" accuracy. Currently, only data about axial and radial touch directions have been published, together with methods for compensation of probing errors. Paper [Choi 2004] describes compensation of radial errors of probes by OMM methods. The key note paper [Sartori 1995] with other 60 references describes other error measurements and compensations. Main task of RCMT was to find and test probes with minimum "trefoil" errors and analyze their multidirectional accuracy by replacing the circular, "equatorial" diagrams with "spherical" representation.

Software methods had to be found and verified for compensation of linear and rotary displacements of workpieces in the working space of machines, caused by temperature dilatations of machine frames. Most of these errors could be eliminated by application of Renishaw "bestfit" program procedures, performing general space co-ordinate transformations of data.

A new software system had to be found or developed which would be able to generate partial measuring programs for selected angular position of the workpiece, combine them together, produce data for control linear and angular NC movements and apply "bestfit" procedure for minimization of thermal errors.

3. Machines used for research of OMM

Measurements were performed on three high-precision milling machines located in the RCMT laboratory and in the IPT Aachen laboratory. These being the type LM-1 vertical three-axis milling machine shown in the Figure 1, the type LM-2 horizontal three-axis milling machine shown in the Figure 2, and the type Nano-Focus five-axis milling machine shown in the Figure 3.

All three machines are equipped with high-speed motor-spindles, with linear motors and with Heidenhain measuring scales for the

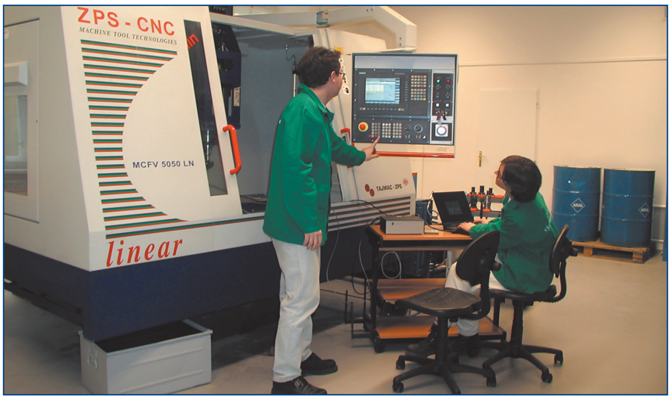

Figure 1. *The type LM-1 vertical milling machine in the RCMT laboratory.*

Figure 2. *The type LM-2 horizontal three-axis milling machine in the RCMT laboratory.*

Figure 3. The type Nano-Focus five-axis milling machine in the IPT Aachen laboratory.

highest accuracy and sensitivity of NC movements. Identical, type Sinumerik 840D control systems of the latest versions were applied. The type Nano-Focus five-axis machine has horizontal a spindle placed in a quill for generation of movements in Z and Y axes and is equipped with a rotary and tilting table moving in X axis and performing rotary and tilting movements in A and B axes. Direct high-torque motors drive rotary A and B axes. Temperature dilatations of the machine are minimized by intensive cooling of the frame.

4. Multi-directional accuracy of touch probes

Figure 4 shows the measurement of multi-directional accuracy of touch probes on the Nano-Focus machine in the IPT Aachen. A high-precision calibrating ball with errors under 50 nm is touched by a touch probe of any type from various space directions.

Figure 5 shows simulation of "bestfit" effects eliminating influence of thermal dilatations on a part with hardly accessible surfaces.

Figure 6 shows spherical characteristics of two different types of trigger touch probes. Complex measuring program is performed at different angular positions with respect to the calibration sphere.

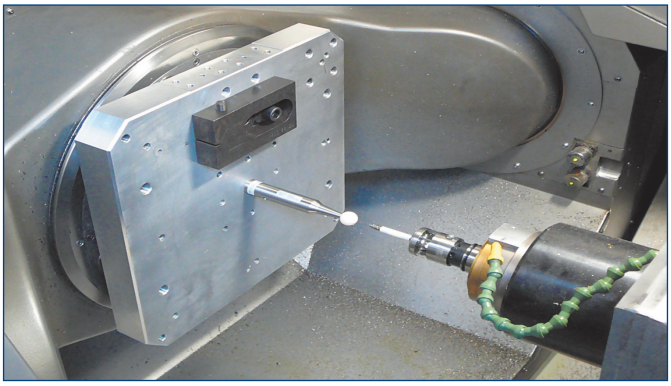

Figure 4. Measurement of multi-directional errors of touch probes on the Nano-Focus machine.

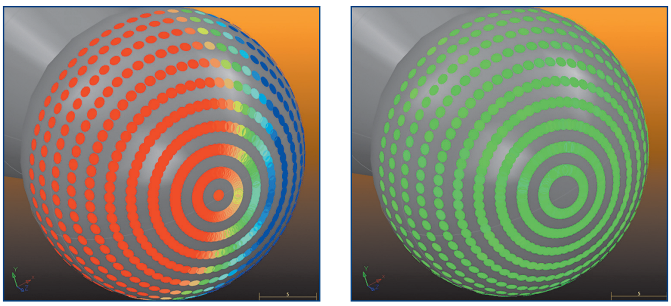

Figure 5. Effect of the "bestfit" procedure on minimization of displacement errors caused by thermal dilatations: (a) before "bestfit", (b) after "bestit".

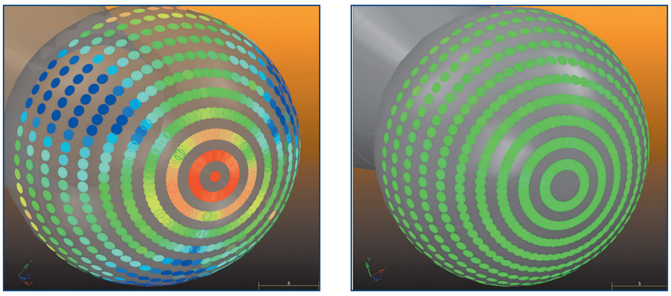

Figure 6. Colour-coded spherical representation of touch probe errors measured in 601 space directions: (a) mechanical probe, (b) tensometric probe.

High-sensitivity of machine movements makes it possible to get reliable data about multidirectional errors of applied touch probes. Figure 7 shows circular, "equatorial" diagrams of two types of probes these being the type TX/RX 40.00 (m&h) mechanical probe with stylus supported in three points and the type OMP400 tensometric touch probe of Renishaw provenance. Diagram of the mechanical probe shows expressive "trefoil" effect, causing the radial approach errors in a range of 12µm, whereas the diagram of the tensometric probe has nearly ideal circular shape in a range of 1.5µm.

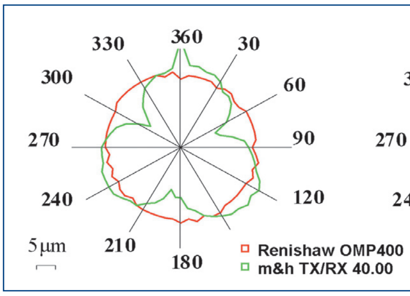

Figure 7. "Equatorial" diagrams of mechanical and tensometric probes.

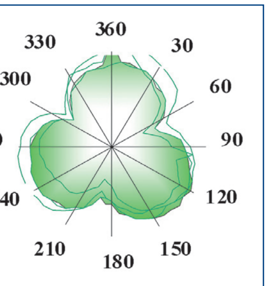

Figure 8. Equatorial diagram showing poor repeatability of mechanical probes.

Moreover, repeatability of measuring data is very poor for mechanical touch probes as shown in the Figure 8. This poor repeatability makes the software compensation of errors rather problematic. Tensometric probes with their perfectly circular diagrams can eliminate superfluous calibrations and reduce the time needed for five-axis OMM cycles.

5. On-machine inspection systems

a. Three – axis measurement systems

During the Hardprecision project, the RCMT worked on the task to develop and verify a three/axis on-machine measurement system for high-precision workpieces. For most of common workpieces, all measuring points can be approached by the touching probe at one suitable angular position of the workpiece and, in case of the Nano-

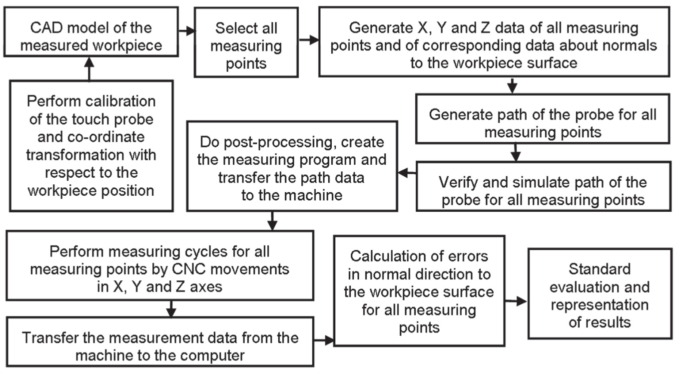

Figure 9. Basic block diagram of the 3-axis measuring system, finalized in the RCMT laboratory

-Focus machine tool, the A and B axes can be kept stationary during the whole on-machine measurement procedure. In other cases, the workpiece should have suitable reference surfaces, which can be approached at two or more independent angular positions of the rotary and tilting table. Than, some sequentially performed 3-axis measurements can create satisfactory data for complex evaluation of errors in all selected measuring points.

Within the Hardprecision project, the RCMT was supposed to finalize and verify similar 3-axis measurement methods by using their 3-axis CNC milling machines equipped with precise measurement systems and highly sensitive linear motor drives.

Types LM-1 and LM-2 milling machines have been adapted for highest sensitivity of NC movements. Analysis and comparison of Renishaw and m&h products has shown much higher accuracy of Renishaw touch probes, so that the OMM systems have been finalized in the RCMT laboratory by application of Renishaw products. Until the end of the 2006, first fully satisfactory results with on-machine measurement of basic geometric shapes have been achieved by application of Renishaw touch probes and software. Fig. 9 shows the block diagram of the 3-axis measurement system finalized and tested in the RCMT laboratory.

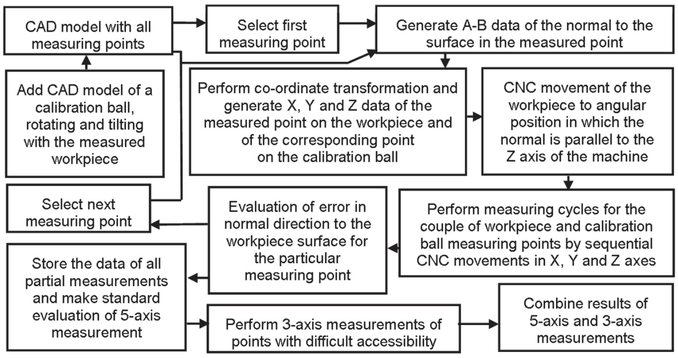

Figure 10. Simplified block diagram of the m&h 5-axis measuring system for complex surfaces.

b. Five – axis measurement system

Special feature of this system is the automatic CNC controlled rotation and tilting of the workpiece to angular positions, in which the normal in just measured point would be parallel with the Z axis of the machine. This means, that the touch probe, moving in the Z direction, touches the workpiece always with its frontal part and accuracy of measurement will not be influenced by deviations of the probe characteristic from the exact spherical shape. Fig.10 shows the simplified block diagram of the m&h five-axis measuring system.

On the other hand, the system may bring about some problems. Measuring points on workpieces with concave shapes and grooves may not be accessible by this five-axis method and a combination with 3-axis measurements will be inevitable. Then, the deviations of the probe characteristic may come into effect and may introduce discrepancies between both measuring methods. Certain time problem can arise with calibration of the touch probe, mechanically connected with the workpiece. Calibration has to be repeated at any movement in rotary or tilting axis, which can happen at every measuring point on a complex surface.

This introduces problems of measurement economy, because it considerably prolongs the time of measurement. This is true especially for cases, where the rotary and tilting axis have to change the probing position for each measuring point.

In such cases, the calibration of the probe on a calibration ball moving with the workpiece is necessary. This actually means that instead of measuring one single point we have to measure another five points on calibration ball. Moreover, the touch probe has to travel from the currently measuring point to the calibration ball, which brings above another loss of time.

c. "Three and two"- axis measuring system

Automatic CNC control of the rotary and tilting table of the Nano-Focus five-axis milling machine makes it possible to combine several partial 3-axis measurements into one preprogrammed, simulated and verified automatic measuring cycle, which would produce final file of data for standard evaluation and graphic representation of workpiece errors at good accessibility from all five directions. The "best fit" program, which was originally only applicable in partial 3-axis measurements for compensation of machine thermal dilatations, will now be applicable for the final complex file of workpiece errors. Number of movements in rotary and tilting axes and number of calibration procedures will be reduced to minimum. Each partial 3-axis measurement may involve an additional calibration for compensation of positioning errors in rotary axes and may involve any number of measuring points. The system is called "three and two"-axis measuring. Figure 12 shows its simplified block diagram.

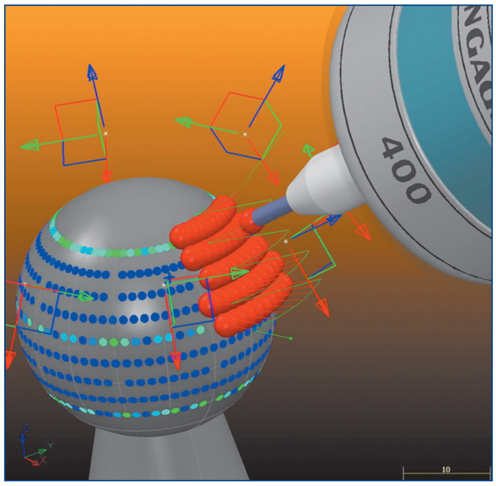

Figure 11. Simulation of five-axis measuring at sequentially applied different inclinations of the touch probe.

The system applies the latest type OMV 4.315 software and type OMP 400 tensometric touch probes, both of Renishaw provenance. Automatic CNC control of rotary and tilting machine movements made it possible to combine several partial 3-axis measurements into one automatic measuring cycle, which produces final file of data for complex evaluation and graphic representation of workpiece accuracy. The "bestfit" program, originally applicable only for partial 3-axis measurements is here applicable on the final complex file of workpiece error data for compensation of machine distorsions. Number of rotary and tilting movements and number of calibration procedures can be optimized and reduced to minimum, as the system can rely on high accuracy of these movements and uses any approach directions of the probe. Simulation, verification and safety control are included and can be applied in all phases of program preparation.

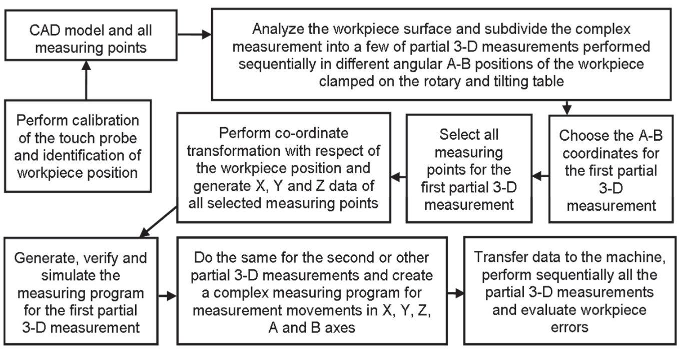

Figure 12. Simplified block diagram of the Renishaw 3+2 axis measuring system.

6. Simulation of measuring cycles

Figure 13 shows computer simulation of measuring touch probe paths with unwanted collision between a stylus of the touch probe and adjacent part element.

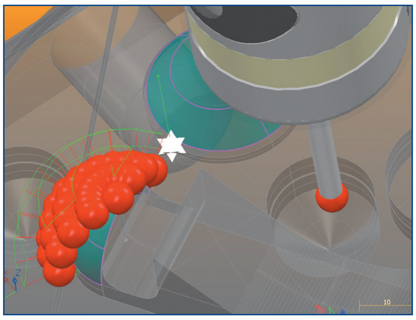

Figure 13. *Simulation of measurement with detected collision in programmed touch probe paths.*

Simulation of OMM for testing part of the Hardprecision project is shown in the Figure 14. This workpiece consists of several identical surface sections, which are measured successively in partial measuring cycles at different angular positions of this workpiece.

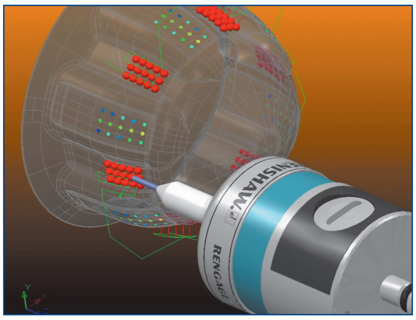

Figure 14. *OMM simulation for Hardprecision testing part with measured set of points.*

7. Measuring of testing workpieces

Figure 15 shows OMM measuring of a testing workpiece with hardly accessible surfaces, produced on a five-axis milling machine in the RCMT. OMM measuring of a testing workpiece NCG 2004 HSC with 2D and 3D elements is shown in the Figure 16.

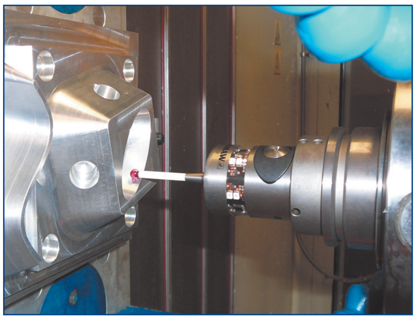

Figure 15. *Measurement of conical surfaces machined by five-axis milling technologies.*

Figure 17 shows real measurement of prismatic workpiece with deep grooves on the Nano-Focus five-axis machine tool in the IPT Aachen laboratory immediately after finishing milling operations.

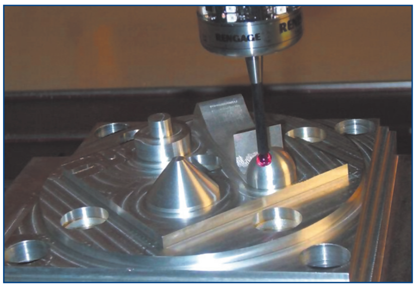

Figure 16. *OMM of hemispherical surface of the NCG 2004 HSC test workpiece in the RCMT laboratory.*

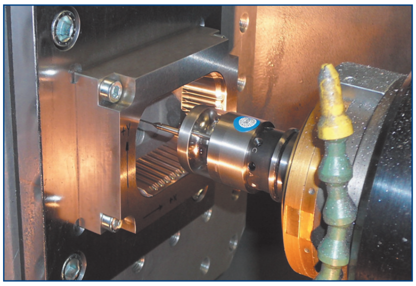

Figure 17. *OMM tests of the Hardprecision testing part with deep grooves in the IPT Aachen laboratory.*

8. Summary

A new five-axis inspection system for automatic on-machine measurement of complex and precise parts has been completed and tested by the RCMT. Control of rotary and tilting measuring movements made it possible to join several partial 3-axis measurements into one automatic five-axis measuring cycle.

Number of programmed calibration procedures has been reduced to minimum, as the system applies various approach directions of the probe to the inspected workpiece.

Application of "bestfit" procedures in final phase of data processing eliminates influence of thermal dilatations and other distorsions of machine tool frames

New software for testing of multi-directional "equatorial" and "spherical" accuracy of touch probes has been developed and verified. The system uses probes with best repeatability and multi-directional accuracy rather than software compensation of errors.

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